Operations Research and Analysis

## A Preview of the Report

# *Development of Airspace Sector and Encounter Models to Support the Analysis of Aircraft Separation and Collision Risk*

NEXTOR Research Report RR-98-16
A. A. Trani and H. D. Sherali (Principal Investigators)
J.C. Smith, S. Sale and C. Quan (Graduate Research Assistants)
Virginia Tech
Blacksburg, VA 24061
November 1998

Prepared by
Stephen Cohen
Investment Analysis and Operations Research
Federal Aviation Administration
Washington, DC 20591
November 1998

## Acknowledgment

This paper provides an overview of, and is based on material in, the report

*Development of Airspace Sector and Encounter Models to Support*
*the Analysis of Aircraft Separation and Collision Risk*

by

A. A. Trani, H. D. Sherali, J.C. Smith, S. Sale and C. Quan
Virginia Polytechnic Institute and State University
NEXTOR Research Report RR-98-16
November 1998.

—Stephen Cohen, editor

The Virginia Polytechnic Institute (VPI) Airspace Occupancy Model (AOM) estimates three-dimensional airspace occupancies and provides input to the Airspace Encounter Model (AEM) described later in this report. AEM models aircraft encounters, generating data on encounter geometries. AOM and AEM have wide applicability, but for the purpose of exposition, the description below is in terms of their use in modeling sector occupancy and conflicts. Both modeling tools generate results mathematically and thus avoid the problems inherent in outputs of discrete, time-step simulation models. AOM and AEM are coded in Matlab™ and can be executed, without modification, in practically any operating system in use today

The main routines of both models are shown in Figure 1. In general, the model converts flight plans or flight tracks into mathematical terms and scrutinizes each flight trajectory over mathematically defined regions of airspace to determine sector crossings and occupancies over time. The model provides graphical outputs of sector occupancies and generates data structures used to analyze pairwise aircraft encounters, such as conflicts and collisions.

## AOM Model Assumptions

AOM incorporates the following assumptions:

- All flights are assumed to fly along straight lines between way-points. (Dummy way-points could be specified to further discretize curvilinear flight trajectories.)
- Two nodes which are less than 0.35 nautical miles apart are assumed to define the same point in the airspace. This assumption is made to correct for inaccuracies in data that sometimes assign different slightly perturbed locations to the same node, and hence create vacuums within the airspace.
- A flight that moves along a common boundary of sectors (or other airspace regions) is assumed to pass through only one of them. The choice is made based on selecting the currently occupied sector, if applicable, or arbitrarily otherwise.

AOM requires a series of aircraft flight plans and sector geometries as inputs. The model processes the information to determine the occupancy of each sector by different flights over time. The model stores the adjacency information of sectors, and identifies the sectors crossed by a flight plan. The Airspace Encounter Model (AEM) uses the outputs of AOM to conduct, for example, “microscopic” evaluations of all possible aircraft blind flying conflicts[1] (or other types of encounters) in every airspace sector. In this example, the outputs of AEM are conflict geometry statistics. The inter-relationships between these models are illustrated in Figure 1. AOM analyzes individual flight paths from an origin to a destination airport and estimates time traversals over each sector encountered.

[1] Blind flying conflicts are conflicts that result from planned flight paths when no intervention by controllers or pilots occur.

This output is then used by AEM to estimate the number of times aircraft pairs could be in conflict if blind flying occurs and the geometries of each of those conflicts.

AOM Flight Plan Generation

The flight plan inputs to AOM can take three forms: 1) flight plans filed by pilots for a given day (ETMS data), 2) flight tracks extracted from SAR data, or 3) flight plans predicted by a flight plan generator such as the NARIM OPGEN (National Airspace Resource Investment Model Optimized Trajectory Generator). There are common elements in all these data sources and, in general, a flight plan should contain the following information.

1 Way-points in latitude (degree), longitude (degree) and altitude (hundreds of feet).
2 Time tags corresponding to the crossing of each of the above way-points (during any time interval).
3 The originating airport (a three letter airport designator). (Optional)
4 The destination airport (a three letter airport designator). (Optional)

The flight plans for any particular day in the past can be obtained from the FAA En route Traffic Management System (ETMS) database or from the Sector Design and Analysis Tool (SDAT) database. In order to use the model to analyze predicted air traffic, an independent flight generator that develops flight plans having the above-mentioned four attributes could be coupled with ASOM.

AOM Airspace Sector Description

Sectors are well-defined airspace regions specified by the FAA for regulating air traffic. Each sector is comprised of one or more Fix Posting Areas (FPAs) and each of these FPAs is made up of one or more modules. A module is a convex or non-convex airspace polytope shape defined by its vertices and its floor and ceiling altitudes. Modules are stacked one over another to form an FPA, and several such adjacent FPAs form a sector as shown in Figure 2. The main source of en route and TRACON sector information used to date in ASOM analyses is the FAA ACES (Adaptation Controlled Environment System) database.

AOM Occupancy Determination

A flight that crosses a sector will be detected by the model based on the adjacency information that is generated and stored during the pre-processing step. Since each sector is complex in shape, the analysis is done at the module level and the results then translated to the sector level. A flow chart illustrating the sector occupancy determination methodology is shown in Figure 3.

The procedures implemented in ASOM can be summarized into four steps: data input, pre-processing, processing, and post-processing. Data input reads flight plan (or track) and airspace sector data from an external source. Pre-processing refers to the creation of mathematical airspace boundaries including dummy sectors and vertex matching. Processing identifies sectors pierced by each flight and sector traversal times. Post-processing refers to the aggregation of flight traversals per sector and the computation of sector occupancies. These steps are illustrated in Figure 3.

The details of the model operation are too complex to be described here. The interested reader should consult the report *Development of Airspace Sector and Encounter Models to Support the Analysis of Aircraft Separation and Collision Risk* [R1].

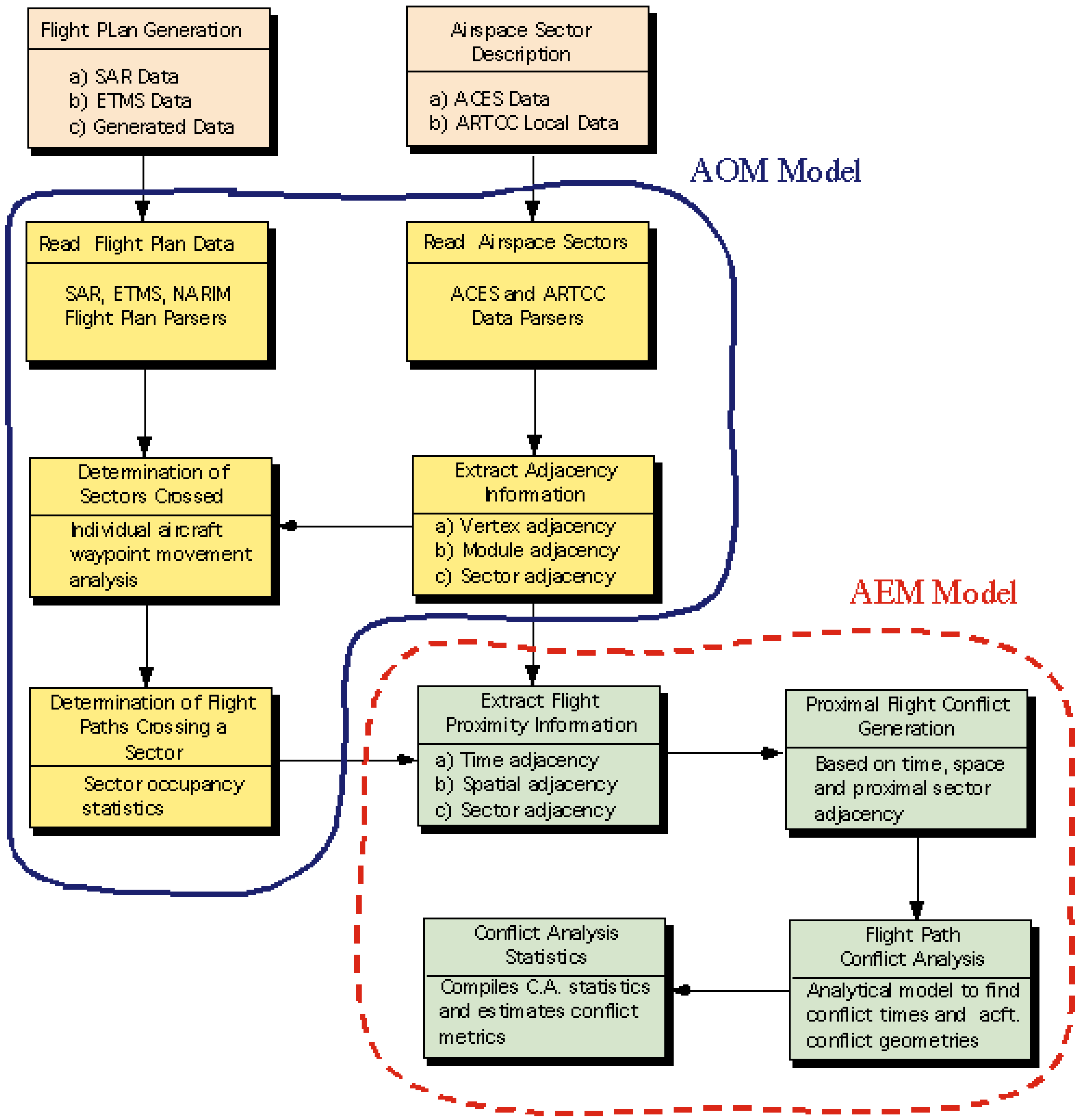


Figure 1.
Airspace Occupancy (AOM) and Airspace Encounter (AEM) Models.

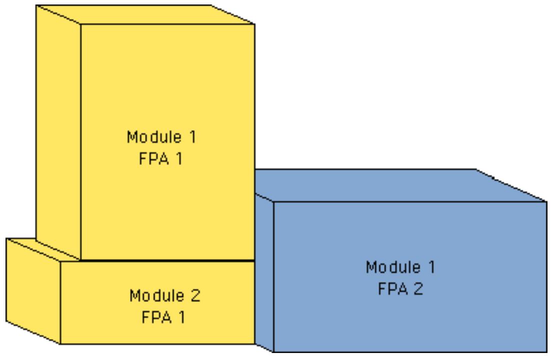


Figure 2.
Typical Sector Geometry (showing a sector made up of two FPAs).

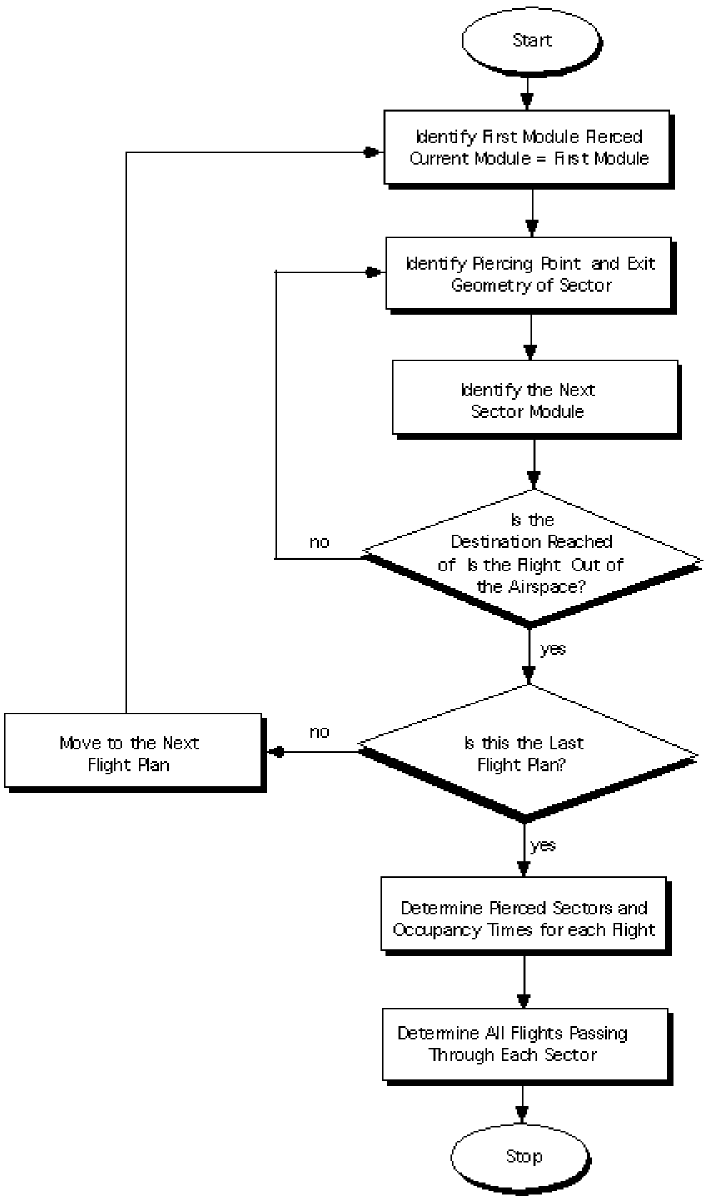


Figure 3.
Occupancy Determination Flowchart.

The Airspace Encounter Model (AEM)

The Airspace Encounter Model (AEM) was developed to estimate blind flying conflicts, collisions, and other encounters related to aircraft relative positions and velocities in NAS airspace. For this discussion, the use of AEM is described in terms of conflict modeling.

AEM can be used to model aircraft conflict patterns under new concepts of operation. For example, AEM can use the output of AOM to determine all potential conflicts among aircraft pairs occurring in a prescribed volume of airspace. AEM records the precise geometries of these conflicts, which can then be used in analyses of collision risk. The FAA/Eurocontrol Separation Safety Modeling Group identified conflict geometry and scenario evaluation as one of the basic tasks needed in modeling collision risk.

The main blocks comprising AEM are shown in Figure 4. The two external blocks in this figure are inputs from AOM. These blocks, shown outside the dotted line boundary of AEM, estimate: 1) sector occupancies and flight path structure and 2) adjacency information to locate spatial relationships between neighboring sector modules.

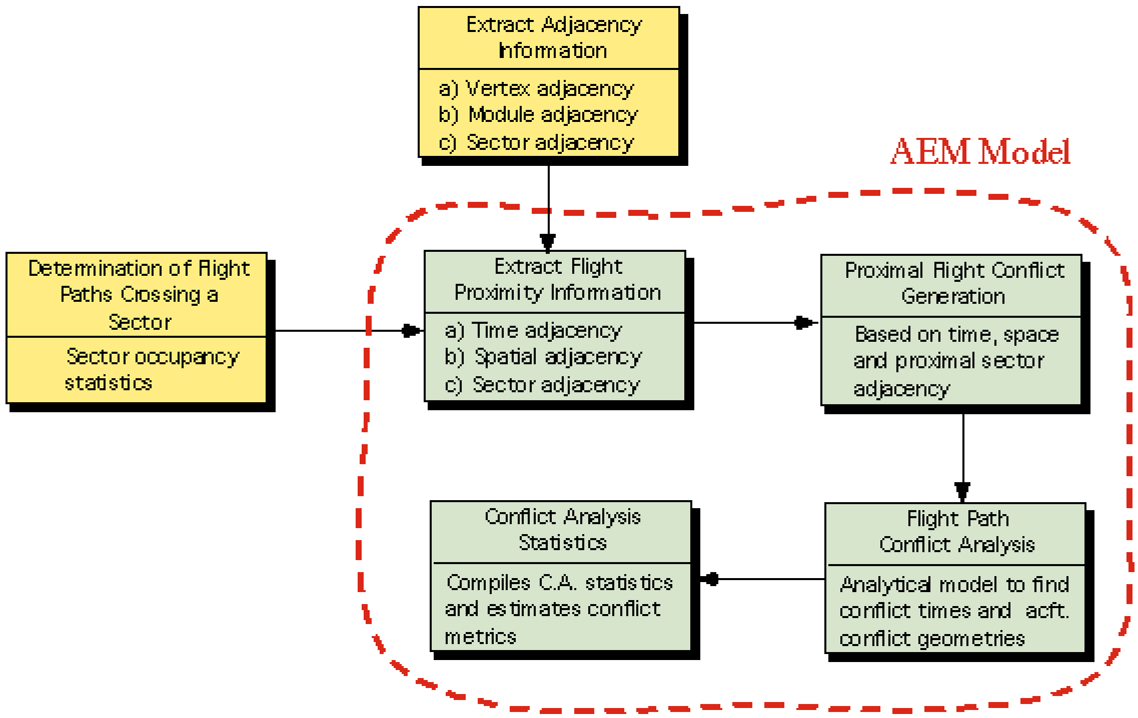


Figure 4. Airspace Encounter Model Block Diagram.

The first major task in AEM is the extraction of flight proximity information. This is done through the creation of three data structures containing time, spatial, and sector adjacency information. The next block extracts proximal flights in time and space and initiates the flight conflict analysis. Once individual aircraft pairs are studied in detail using analytic trajectory equations, suitable conflict analysis statistics are collected and aggregated.

Aircraft trajectories in AEM are modeled using basic principles of spherical geometry. A description of the details of the methodology may be found in [R1]. The modeling combines spherical geometry modeling with a generalization of the box-model of Reich [R2] that examines rectangular envelopes and proximity shells as illustrated in Figure 5. Here, $S_1$, $S_2$, and $S_3$ respectively denote the standard in-trail (along track), lateral (across track), and vertical separation parameters, and $D_1^A$, $D_2^A$, and $D_3^A$ denote the proximity shell-based separation requirements in these three respective dimensions for some particular (type of) aircraft *A*. Note that AEM can utilize any mathematically-describable shape, and the aircraft need not be centered in the shape.

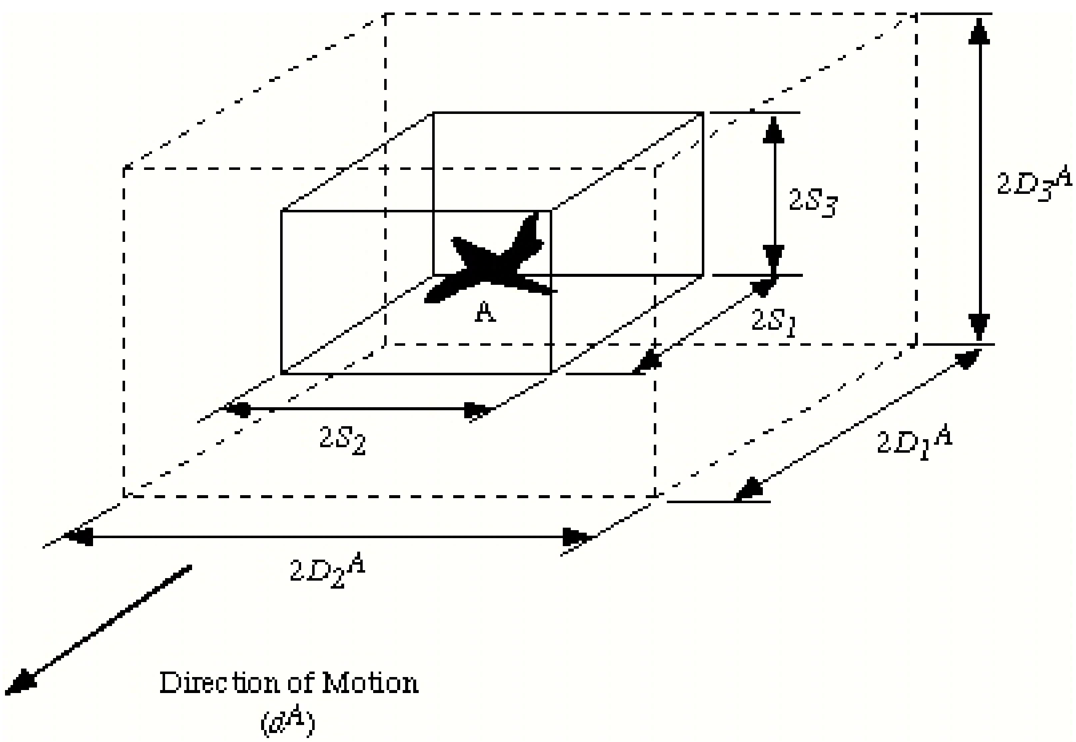


Figure 5.
Standard Envelope and Proximity Shell for Aircraft A.

When an intruding aircraft *B* (treated as a point or "*particle*") lies within the proximity shell, there exists a *conflict risk*. When aircraft *B* enters the inner box, this represents an *untenable conflict* that must be resolved. (A *fatal* conflict could be described via another innermost circumscribing box around the aircraft, if necessary.)

The intensity of any conflict can be classified according to the actual (minimal) separation distance while the intruder is within the proximity shell, the duration of this intrusion, its entry and exit faces, and the relative velocity and relative heading of aircraft *B* with respect to aircraft *A*. The computations are rather complex and so are omitted here. They may be found in [R1].

As mentioned above, AEM can be used in analyses involving nonlinear envelopes and proximity shells. For instance, discs with ellipsoidal cross-sections could be used as aircraft proximity shells with the aircraft not centered in its shell. For example, along the in-trail direction, a greater separation might be required ahead of the aircraft than behind it.

<u>Summary of the Conflict Analysis Methodology</u>

Sector occupancy durations are first computed for each flight. A list of sectors entered by each flight is compiled, along with the times at which the flight enters and exits these sectors. Also, for each sector a list is compiled of all flights which traverse that sector, along with their entering and exiting times.

Since testing each distinct pair of flights for conflicts is computationally expensive, logical tests are performed to eliminate pairs of flights which cannot conflict. Preprocessing is therefore conducted to determine all pairs of flights which occupy the same sector or adjacent sectors at the same time. These flights are recorded for performing a more detailed conflict analysis during the intervals in which they may possibly conflict.

For each flight *i* in sector *s*, let $I^s(i) \equiv [d^s(i),a^s(i)]$ denote the interval between the entering and exiting time for *i* in *s*. Only flights which occupy *s* or the sectors *neighboring s* for a time interval overlapping $I^s(i)$ may conflict with *i*. For each sector *s*, a set of *neighboring* sectors is specified such that the only possible conflicts that can occur with a flight that occupies sector *s* are with respect to flights that simultaneously occupy some sector in this set of neighbors. These neighboring sectors are found by constructing a rectangular box which encompasses *s* plus a buffer area such that if a flight does not lie within this box, it may not conflict with a flight in *s*.

A rectangle is constructed around the two-dimensional cross section of *s* and then extended into three dimensions by examining the floor and ceiling of *s*. First, the geometric center *c* of *s* is found (by taking the average of the defining vertices of *s*), and the largest distance from *c* to any vertex of *s* is determined. This longest distance becomes half of the length of the rectangle, with the other half extending in the opposite direction from the center. Each vertex is then examined on either side of the line that passes through *c* and is parallel to the side of the rectangle that defines its length. The rectangle is then widened as necessary on either side of this line to include each vertex (see Figure 6). This rectangle, which encloses all the defining vertices of *s*, is then enlarged to include the buffer space, which should be the distance from the center of the protective box enveloping the largest aircraft to one of its corners. The protective box used is the one based on the standard separation criteria. Finally, the floor of this rectangle is set at the maximum of zero and the floor of the sector minus the buffer space, and the ceiling is set at the ceiling of the sector plus the buffer space.

Once this rectangular box has been constructed, any sector intersecting this box is included in the set of neighbors of *s*. Each defining vertex of a sector is tested for its inclusion within the two-dimensional rectangle. If a vertex is found to be within this rectangle, a separate check is performed to determine if it also lies within the floor and ceiling of the rectangular box. For any vertex *v* which is found to meet these criteria, all sectors which include *v* on their boundaries are included in the set of neighbors of *s*.

Hence, for any other flight plan *j*, if *j* exits *r* before *i* enters *s* ($a^r(j) < d^s(i)$), or if *i* exits *s* before *j* enters *r* ($a^s(i) < d^r(j)$), for each sector *r* equal to or neighboring sector *s*, flights *i* and *j* are not airborne in a close vicinity of each other at the same time, and need not be considered in the conflict analysis. Otherwise, the interval during which a conflict may exist, *C*, is computed, and a conflict analysis for flights *i* and *j* is performed over *C*. The record $[i,j,I^s(i)]$ is added to *CA*, the list of flights and durations for which a conflict analysis is to be performed.

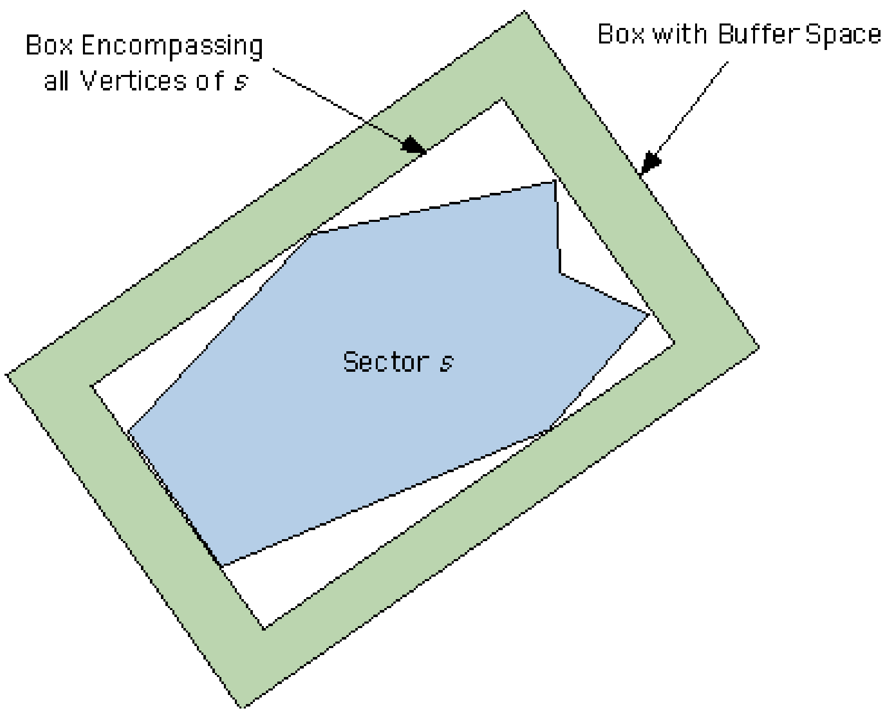


Figure 6.
Illustration of 2-D Rectangle Created for Neighboring Sector Analysis.

Following this preprocessing, the list *CA* is passed to the conflict analysis routine. A conflict analysis is performed on each pair of flights for the given times in which the flights may possibly conflict. The conflict analysis routine considers the flights along each linear segment of their trajectories (as defined by their way-points.) Since conflicts are not considered below 10,000 ft, and since the size of the protective box changes at

29,000 ft, extra way-points are created at these altitudes if necessary (along the corresponding linear segments) that pierce these altitudes.

Each entry of *CA* is considered independently, with each possible conflict being passed to the conflict analysis routine. For a given entry $[i,j,I^{s}(i)]$ of *CA*, the conflict analysis routine inserts the extra way-points at 10,000 ft and 29,000 ft, and also at the beginning and ending times of $I^{s}(i)$. The conflict analysis considers each linear segment between way-points traversed during the interval $I^{s}(i)$. For a given pair of flight segments, if the altitude of either aircraft is below 10,000 ft or if the two aircraft are sufficiently separated by altitude, then no analysis is done for that pair of segments. Otherwise, the procedure determines the size of the protective box around the primary aircraft based on the altitude of the primary aircraft, and a detailed analysis begins. The detailed conflict analysis procedure indicates whether or not a conflict exists, and reports the class of the conflict in terms of the faces around the aircraft entered and exited, the relative heading of the conflict, the duration of the conflict, and the minimum distance at the closest point of approach. Note that although *CA* only lists potentially conflicting aircraft $i$ and $j$ such that $i < j$, the conflict analysis must be performed twice, considering each aircraft as the primary aircraft.

The resulting output is then sorted first by primary aircraft, next by secondary aircraft, and finally by the starting time of conflict to obtain a list describing the ongoing conflicts encountered by each aircraft. Note that for conflicting flights $i$ and $j$, there may be many records describing the same conflict if the conflict continues over several linear segments. The overall conflict between $i$ and $j$ may be summarized by conglomerating all consecutive records of conflicts between $i$ and $j$ such that the ending time of one record corresponds to the beginning time of the next record. For this set of records, the maximum conflict severity, minimum separating distance, direction of flight while approaching the minimum separating distance, and the overall length of conflict duration are recorded and used to compute overall aggregate metrics.

## References

**R1.** Trani, A. A., H. D. Sherali, J.C. Smith, S. Sale and C. Quan, *Development of Airspace Sector and Encounter Models to Support the Analysis of Aircraft Separation and Collision Risk*, Blacksburg, VA: Virginia Polytechnic Institute and State University, November 1998, NEXTOR Research Report RR-98-16. [Report is available at *www.ce.vt.edu/nextor/collision.html* , *http://www.faa.gov/opsresearch/reportor.htm* , or at *www.its.berkeley.edu/nextor/html/research_projects.html* .]

**R2.** Reich, Peter G., "Analysis of Long-Range Air Traffic Systems: Separation Standards--I, II, and III," *The Journal of (the Institute of) Navigation,* Vol. 19 (1966), No. 1, pp. 88-96; No. 2, pp. 169-176; No. 3, pp. 331-338.